

# Recent development of arch bridges in China

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**ABSTRACT:** Arch bridge has a long history with high prestige in China. In the 20th century, the arch bridge still played a leading role with its great variety and large magnitude, especially in highway bridges. With the continuous economic development since 1980s, numerous bridges have been built, including a large number of arch bridges accompanying with the development of material, construction methods as well as design theory. At present, China keeps all the span records of stone, steel, reinforced concrete and concrete filled steel tubular arch bridges by New Danhe Bridge (stone arch bridge with a main span of 146m), Choatianmen Bridge (steel arch bridge with a main span of 552m), Wanxian Yangtze River Bridge (concrete arch bridge with a main span of 420m and Wushan Yangtze River Bridge (CFST arch bridge with a span of 460m).

## 1 INTRODUCTION

In the past 30 years, China has mobilized a program of large scale bridge construction. By 1978, China had 128210 highway bridges with a total length of 3283 km, and 26139 railway bridges with a total length of 1099 km. In the past three decades from 1979 to 2008, bridge construction averaged 16000 bridges per year. By the end of 2008, there are 594604 highway bridges in China with a total length of 25240 km, and 52355 railway bridges with a total length of 4349 km. Among these bridge, many are large span bridges, such as cable-stayed bridges, suspension bridges and arch bridges .

China has a long history of application of arch bridge and has achieved high prestige in the world. In 20th century, the arch bridge still held the leading role with its great variety and large magnitude, especially in highway bridges. A statistics shows that around 30% of highway bridges are arch bridges until 1990s. Among these arch bridges, most of them are stone and reinforced concrete arches. Because of cheap cost in labor and stone and concrete material, stone or reinforced concrete arch bridges were economic to be built for a long time until 1980s. In the recent 30 years, despite of the fact that more modern PC girder bridges, cable-stayed bridges and suspension bridges are used as solutions for long span bridges, arch bridge is still a structural type of large actuality and application to modern construction technologies in China. At present, China keeps all the span records of stone, steel, reinforced concrete and concrete filled steel tubular arch bridges in the world. The paper introduces the recent development of arch bridges in China with recommendations.

## 2 STONE ARCH BRIDGES

China has a vast territory with many networks of rivers. Throughout the history, the Chinese nation has erected thousands of bridges. Among them, some stone arch bridges survived to today, such as the ChawZhou Bridge. Stone arch bridges were adopted widely in highways in 1950-1970s. Even at present, they are also used in hilly or mountainous areas. The Wuchaohe Bridge with a main span of 120m, located in Hunan Province, is built in 1990. New Danhe Bridge, located in Shanxi Province and opened to traffic in 2000, is a stone arch bridge with a span of 146m and deck width of 24.8m (Fig.1). The thickness of section is 250cm at the arch crown and 350cm at the arch spring. It ranks as the world's longest span stone arch bridge.

However, stone arch is completely unstable until the arch rib is enclosed. Therefore, it should be built by elaborating scaffolding, or "centering," below the spans to support them during arch rib construction. In many cases, it is not an economic bridge type to be considered. After 1990s, only four stone arch bridges with a span larger than 100m have been built.



Figure 1 : New Danhe Bridge in Shanxi

On the other hand, many stone arch bridges are still in service in the road system. Long service time, poor conditions and increasing traffic are making more and more harm to the existing masonry arch bridges. The maintenance, rehabilitation and strengthening of these stone arch bridges have become a very important topic in China. Bridge management authority and engineers should pay enough attention to these issues and learn from research results and engineering experience practised in other countries. Just in the proceedings of past international conferences on arch bridges, there are many papers focusing on these aspects.

### 3 STEEL ARCH BRIDGES

In China, for a long period, steel products per person were very little; so only few steel arch bridges had been built before 1980. During century transition period, the steel arch bridge and composite arch bridge began to develop very fast.

On June 28, 2003, the Lupu Bridge was open to traffic (Fig.2). This bridge in Shanghai with a main span of 550m, crossing the Huangpu River, is the longest span of arch bridge in the world, 32m longer than the 518m-long New River Gorge Bridge, West Virginia, United States.

The bridge was constructed with a bold idea to use “suspended basket arch” structure of more aesthetical looking. It is a big challenge to make cantilever erection of arch rib segments with a weight of around 480t on inclined arches. A half-through tied-arch bridge was chosen as it suits the particularly soft soil foundation conditions in Shanghai. In order to balance the huge thrust of the main span, structural system transformation was made several times during construction to transfer tension in temporary cables to cables for suspenders. It is a creative idea to carry out construction control from beginning to the end of construction.

The span arrangement of Lupu Bridge is 100+550+100m. The arch rise is 100m and the rise to span ratio is 1/5.5. Each of the twin steel box arch ribs has a width of 5.0m and a depth of 6m at crown and 9m at the arch spring. The arch ribs are connected with both 25 straight bracings above the deck and 8 K-shaped bracings below the deck. Horizontal cables are adopted to balance the horizontal force of the arch .

Construction of the huge six-lane Lupu Bridge began in October 2000 and has cost 2.25 billion yuan (272 million US dollars). The main section of the 3,900m-long bridge is 750m long and 28.7m wide. The 550m-long main arch is made up of 27 box connectors, assembled by jointing, and 28 pairs of hangers linking the bridge deck. Over 35,000 tons of steel has been used in its construction.

The project won the 2008 IABSE Outstanding Structure Award for being “a soaring box-arch bridge with a record span, clean impressive lines and innovative use of the side spans of the arch and the deck to resist the thrust of the main arch”.

After the completion of Lupu Bridge, some steel arch bridges with large spans are under construction or planning in China.

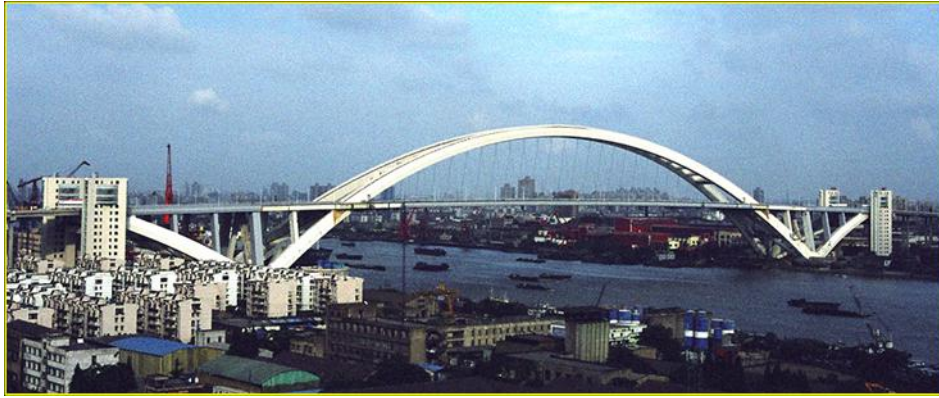


Figure 2 : Lupu Bridge in Shanghai

Caiyuanba Yantze River Bridge, located in Chongqing, is an urban bridge with a total length of 800m. Its main bridge is a three span arch bridge with double decks. The structure is a composite one, consisting of rigid frame, steel truss girder and steel box tied arch ribs and the central span is 420m, each side span is 88m. The upper deck carries six lanes of highway and two pedestrian walkways and the lower deck carries two tracks of monorail. Each of the two steel box arch ribs in the central span upper deck has a span of 320m and a rise of 56m, with a inclining angle of  $10.67^\circ$  towards each other. The rib box has a section of  $2.4 \times 4.0$ m with a various thickness from 24mm to 40 mm. Six steel box bracings connected the two ribs as a spatial structure. Each rib was divided into 23 segments for erection, a standard one has a length of 16m and the heaviest segment is 91.6t. The steel arch ribs of Caiyuanba Yangtze River Bridge were erected by cantilever method with temporary pylons and cables, and the segments of the ribs were hoisted by cable crane. The bridge was opened to traffic on 29 October, 2007. Fig.3 is the photo of the bridge after completed.



Figure 3 : Caiyuanba Yantze River Bridge in Chongqing

Xinguang Bridge, crossing the Pearl River in the city of Guangzhou, has a total length of 1083.2m. The bridge has main spans with a length of 782m in an arrangement of 177m+428m+177m. The main bridge is composed of two PC triangle frames and three steel arches. It has 37.22m wide for six traffic lanes and two side walks.

The arch of the central span has a span of 428m (clear span length: 416m) and a height of 104m, giving a rise to span ratio of  $1/4$ . A arch rib has a depth varying from 7.50m at the crown to 12.0m at the spring. It consists of steel truss rib upper the deck and prestressed concrete rib below deck which is also a member of the triangular frame. Foundations for the main bridge are supported on end-bearing cast-in-place bored piles anchored in solid rock layer. After the triangle prestressed concrete piers were completed, each span steel arch ribs were hoisted by three segments. It was completed in 2006, see Fig.4.



Figure 4 : Xinguang Bridge in Guangzhou

Chaotianmen Bridge is the longest arch bridge in China today and also in the world. The bridge is located in Chongqing City, has a total length of 1741m. The bridge has double decks, of which the 36.5m upper deck has dual three-lane motor ways and sidewalks on both sides, and the lower carries two lanes of municipal light railways and two lanes on either side. The main bridge adopts a cantilever steel truss arch with a span arrangement of 190+552+190m.

The main arch truss with two pieces of truss is 29m wide. All of the main truss members are welded box sections. Two levels of shape steel tie members are set in the central span, at 11.83m spacing. The upper tie is not through the whole main truss and only connected to the lower arch chord; while the lower tie goes through the whole truss including the middle chord at the stiffened leg and the lower chord in the side span. Moreover, for the lower tie, cables are employed to assist the steel shape tie members.

The orthotropic steel plate is applied for both upper deck and lower deck system. The steel plate is 16mm thick, with closed “U”-shape ribs. The support system of main bridge adopts hinged bearing system. The main bridge has spherical cast steel hinged bearing system with maximum bearing capacity of 145000KN.

The Chaotianmen Yangtze River Bridge has been open to traffic on 29th April, 2009, see Fig.5.



Figure 5 : Chaotianmen Bridge in Chongqing

Danqinghe Bridge is a major steel arch bridge in highway. It is located in Wuxia, Wushan, Chongqing, cross Daning River. The main bridge is a steel truss deck arch with 400m long span and 24.5m wide deck, having four traffic lanes in each direction.

The truss arch rib has constant depth of 10m. There are three arch ribs and the spacing between them depends on the calculation results. The top and bottom chords are of steel box section with a constant depth of 1.5m and width of 1.0m with inside longitudinal stiffener.

During construction, each arch rib was divided into 18 segments according to the available lifting capacity. The maximum segment weighed 160t. The wall thickness of the chord is varying from the crown to the spring in accordance with the mechanical requirement, ranging from 30mm to 48mm. The spandrel column is of steel frame structure, corresponding to the three arch ribs.

The deck is supported by continuous steel-concrete composite girders with the span length of 27m. The I-shaped welded girder is 1.7m deep, and its top flange is 16mm thick, bottom flange 26mm and web plate 16mm. The precast reinforced concrete deck plate is 12cm thick.

Reinforced concrete arch seats are designed to have a stepped underside, which is helpful to transfer the force between them and their foundation. Three piles are supported in front of the arch seat. At the rear of the seat, another three piles are inclined 10 degrees to resist the thrust and reduce the displacement of arch seat.

The arch rib of Daninghe Bridge is erected by cantilever method. During construction, the ribs were lifted and positioned by crane, which has the maximum hoisting capacity of 265t. The segment of arch rib is 26m long and 10m high. Fig.6 shows the bridge under construction. The bridge has been completed on 10th October, 2009.



Figure 6 : Daninghe Bridge under construction

At present, the largest steel arch bridge in China under construction is the Dashengguan Bridge, located in Nanjing and crossing the Yangtze River, which is a key engineering project in the High-speed Railway linking Beijing to Shanghai. This bridge will also serve as a two-lane subway bridge for Nanjing City. Eventually, the bridge will carry 6 lanes of traffic loads in two directions with very heavy live loads and a requirement for high speed train.

The main bridge, a composite structure with steel truss arch and steel truss continuous girder, not only provides a favorable appearance, but also meets the requirement for train running with high speed and heavy load. Furthermore, the truss structure is convenient for construction. The superstructure of the main bridge is continuous over six spans: 108+192+336+336+192+108 meters, with the overall length of 1272 meters. Here, the 108m side span is effective to minimize the intersection angle at the end of the girder to ensure the safe running of high-speed train, and to provide convenience for the installation during construction.

There are three truss arch ribs in each span, which is spaced at 15m. The rise of the arch is 84.0m. The depth of the arch rib is varying from 12m at crown to 47.9m at spring. The depth of the river at the position of the piles is approximately 51m, and the whole length of the pile amounts to 112m. The steel cofferdam for the main pier is weighed above 6000t.

To ensure the integrity and stability of the arch rib, the longitudinal connection is installed in the plane formed by the top and bottom chord, the top chord in horizontal truss, and the stiffening chord. The transverse connections are installed in the vertical plane to improve the torsional stiffness. The main arch rib is shown in Fig.7.

The arch ribs have been closed in the August 2009. Fig.8 shows two photos of the bridge under construction. The bridge will be completed and open to train in 2010.

Steel is a material with superior strength and ductility, so it is possible to make the span of arch bridge longer and sometimes it is a good solution for large span bridge, especially for railway bridges because it can provide larger stiffness than cable-stayed bridges. However, stiffness required for steel arch bridges consumes more steel and causes difficulty in fabrication or erection, compared with girder-typed bridges or cable-stayed bridges. This is one of the reasons why only a few steel arch bridges have been built since 1970s in the world. Though many large steel arch bridges have been built in China in a recent decade, building steel arch bridges are still more expensive than other types of bridges. Therefore, it is not economic to build large steel arch bridge if there is not a typical requirement.



Figure 7 : The truss connections in Dashengguan Bridge



Figure 8 : Construction of Dashengguan Bridge

#### 4 REINFORCED CONCRETE ARCH BRIDGE

Many RC arch bridges have been built also in China. From the 1960's to the 1970's, many concrete arch bridges with light self-weight were presented and applied because construction materials were in very shortage at that time, and such arch bridges were suitable to weak soil sites and easy for construction. These bridges include curvature arch bridge, rigid-framed arch bridge, trussed arch bridge and prestressed trussed arch bridge .

In double curvature arch bridge, the arch ring is composed of ribs and bracings, cross curved plates and covering arched plates. They generally are open spandrel arches with reinforced spandrel columns and spandrel arches. The longest one is Qianhe Bridge built in 1968 with a clear span of 150m.

Both reinforced concrete and prestressed concrete truss arch bridges have been built in China. The concrete truss arch bridge is erected by hoisting the prefabricated slices of braced spandrel arch one by one and connecting them through lateral bracings. Limited by the hoisting capacity, the span only reaches to 60m. The prestressed concrete truss arch bridge is built by cantilever method. Jiangjieshe Bridge with a span of 330m is the longest one. The main arch rib is a three-cell box, 2.7m high and 10.56m wide.

In rigid-frame arch bridge, the horizontal members rigidly attached to two main inclined legs with a curved intrados. In a longer span case, two or more inclined subordinate legs are connected to arch seat and the horizontal members. This bridge type is suitable for bridges with medium span. The longest span reinforced concrete rigid-frame arch bridge is the Taibai Bridge with a span of 130m.

During the period when the supply of cement and steel was insufficient, many bridges of these light-weight types were built. However, it is obvious that the bridges designed based on old codes can't satisfy the increasing traffic demand at present. In addition, some structural deficiencies, existed in these bridges, such as poor integrity, easiness to cracking especially in the web joints in double-curved arch rings and rigid joints of the truss arch bridges. Many of them have been rebuilt or even removed. It is seldom to build these types of bridge after 1980. But with regard to a large number of such bridges which are still in service, we should pay more

attention to their inspection, rehabilitation and strengthening.

Thanks to the economic development, many arch bridges with reinforced concrete box rings and ribs have been constructed from 1980. Most of them are deck-fixed arch with RC spandrel columns and simple deck girders. In the meanwhile, erection technologies are developing fast, and longest span record was refreshed continually.

Cantilever method was developed in construction of light concrete arch bridges. By using this method, the Yibin Mamingxi Bridge with a span of 150m was completed in 1979.

From 1975, research on horizontal swing technique in construction of concrete arch bridge was carried out and it was successfully applied in the construction of Shining Bridge in 1977, which is 70m span box-ribbed reinforced concrete arch bridge. In 1989, the Fuling Bridge with a main span of 200m was completed. The three-cell box ring was divided into three parts in construction. The two side cells were erected by horizontal swing method without balance weight. In this method, only the arch ribs on the pivot were rotated to closure. Then two box ribs were connected by casting in-situ to form the middle cell.

Steel scaffolding as reinforcement for concrete arch was first employed in 1983, and some half-through box-ribbed arch bridges were constructed by this method, for example, the Yibin Xiaonanmen Bridge with 240m span. It is noteworthy that large amount of embedded shaped steel scaffolding makes it expensive. In 1996, Yongjiang Bridge (Fig.9) with a main span of 312m was completed, using CFST arch as embedded scaffolding. It is a half-through box-ribbed arch bridge with a width of 18.9m. In construction, the steel tubular truss arch was erected by cantilever method and concrete was filled into steel tubular chords after it was closed to form a CFST arch. Using CFST as embedded scaffolding makes this construction method very economic and the span of concrete arch bridge longer.

The longest concrete arch bridge in the world, Wanxian Yangtze River Bridge, was also constructed by this method, which is a deck box ring arch bridge with a clear span of 420m and deck width of 24m (Fig.10). The main arch rib is a three-cell rectangular box, 7m high and 16m wide. It was completed in 1997.

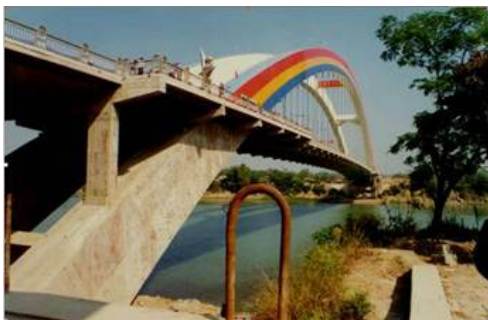


Figure 9 : Yongjiang Bridge

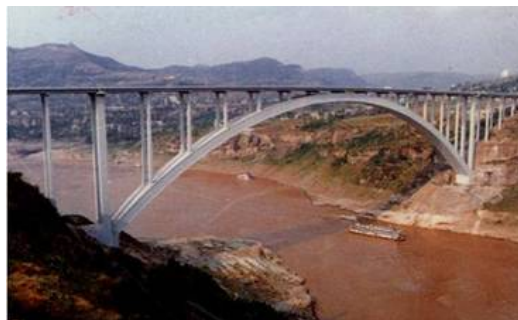


Figure 10 : Wanxian Yangtze River Bridge

A recent statistics of RC arch bridges in China show that in the last two decades (1989 – 2008), 8 RC arch bridges with a span larger than 200m have been built in China; however, only 2 were during the last decade (1999 – 2008). It can be said that the competitive ability of long span RC arch bridges has decreased compared to other type bridges, like girder bridge, cable-stayed bridge and suspension bridge. Even for a site suitable for arch bridge, steel arch bridge or CFST arch bridge are more often to be selected as the solution.

Two key basic problems for long span RC arch bridge application are the heavy self-weight and the construction techniques. In order to promote the competitive ability and encourage the application of RC arch bridge, researches on arch bridge with new steel-concrete composite structure and high strength concrete, advanced construction techniques have been carrying out in recent years in China.

A series of concrete arch structure with steel webs have been proposed and studied in Fuzhou University since 2003. In this new type steel-concrete arch, the arch box section is composed of upper and bottom reinforced concrete slabs and steel webs. The steel web can be corrugated plates, (plane) plates and tubular web members. Trial designs by employing real arch bridges as prototypes and experimental researches of arch models (Fig.11) have been conducted. Research

results show that the self-weight of arch ring of RC-steel web will decrease about 30% compared with the general RC arch ring, and construction will be easier and the days will be saved for free of concreting the webs.

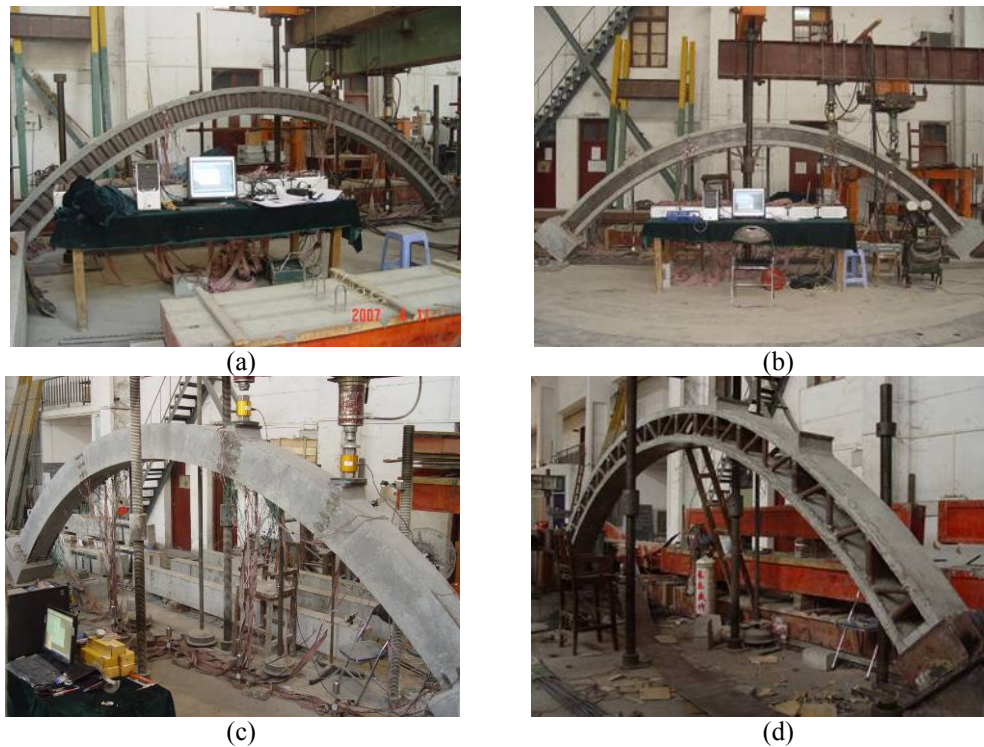


Figure 11 : RC-steel Web Arch Experimental Models: (a) Arch model with corrugated webs, (b) Arch model with plane webs, (c) Arch model with steel truss webs, (d) Arch model with concrete box.

Reactive Powder Concrete (RPC) is a new type of cement-based material with high performance capabilities, such as high strength, high ductility and durability, and low permeability. Therefore, RPC structure can eliminate the need for reinforcing steel, expanding the range of structural shapes and forms for the architect and designer. It has been adopted in some footbridges, such as the Sherbrooke pedestrian/bikeway bridge in Canada, the SunYu Bridge in Korea. In order to apply it to large arch bridge for traffic, trial design and model test are being carried out in Fuzhou University at present .

As for construction techniques of arch bridges, almost all of the construction methods employed in arch bridges in other countries have been adopted in China, such as the scaffolding method, cantilever method, swing method and embedded scaffolding method. Moreover, some innovative methods with high prestige have been proposed and developed, like the horizontal swing method, the embedded CFST scaffolding method. In construction of arch bridges, cable cranes are widely used in China as hoisting devices, which have great hoisting capacity, long span and sometimes with multi-span. However, for long span RC arch bridge, heavy self-weight of the arch ring will rise up the difficulty of the construction whatever construction method is used. Combination of construction methods perhaps is the tentative method to be used, saying cantilever method for the spring parts from two arch seats and embedded scaffolding method for the central part. The construction method for supper long span RC arch bridge is under research both for trial designed bridge and real bridge case.

## 5 CONCRETE-FILLED STEEL TUBULAR(CFST)

Concrete filled steel tubular (CFST) arch bridges have been built in China since 1990. With the trend of increasing the use of steel material and decreasing the labor in bridge construction due to the rapid development of economy, CFST arch bridge became a good alternative to achieve a



kind of balance between reinforced concrete arch bridges and steel arch bridges. In addition, it has a more pleasing appearance. Therefore, many CFST arch bridges have been built in China in recent decades.

As we know, CFST member has higher strength than those of masonry or reinforced concrete and can provide larger stiffness than steel tubes. Under axial compression, an interactive force from steel tube confines the concrete core, which greatly improves the load-carrying capacity and the maximum compressive deformation of the concrete core, and meanwhile the cored concrete also prevents the steel tube from local buckling. As a result, the spans of arch bridges can be lengthened by use of CFST.

Another important advantage of the CFST arch bridges is that the thin-walled steel tubular arch itself can be erected with lighter self-weight and more outstanding stiffness than concrete members or shaped steel members. The erected steel tubular arch can be filled with concrete without falsework and formwork. This makes the erection of arch bridges with long spans possible, improves the construction speed and saves the amount of falsework and formwork.

Since so many advantages from CFST arch bridges, they can meet the requirements of economy, material saving, easy erection and high load carrying capacity. The first CFST arch bridge in China, the Wanchang Bridge with a main span of 110m, was completed in 1990. From then on, more than 200 of such bridges have been built or under construction, in which 16 of them have a span more than 250m .

The structural configuration of all CFST arch bridges is not the same. There are many types of cross-sections used in arch ribs, such as singular tube, dumbbell type and trusses of three to six tubes, etc. Depending on the deck location, there are deck arch, through arch and half-through arch bridges. Both through arch and half-through arch configuration are most widely used in CFST arch bridge in China. The CFST arch bridges can also be classified into lateral bracing, no bracing, lift-basket arch bridges according to lateral connection. Additionally, according to thrust in arch, there are thrust and no-thrust arch bridges. The latter can be further classified into arch-girder system and rigid-frame tied arch system.

The ordinary erection methods used in CFST arch bridges are the cable crane method and the swing method. As for cable crane method, steel tubular arch ribs are divided into several segments. The weight of each segment should be limited within the cable hoisting capacity. Both main and auxiliary cables are used to maintain stability and balance during construction. The segments are erected one by one from the spring towards the crown. This method is sometimes called the launching method. The launching method is being used in many CFST arch bridges, such as Fengjie Meixi River Bridge, Napu Bridge, Wushan Yangtze Bridge, etc.

Another main erection method used in CFST arch bridges is the swing method, which has been rapidly developed in recent years in China. This method includes the vertical swing method and the horizontal swing method. Using the horizontal swing method, two half leaves of arch ribs are fabricated on both banks of the river with their ends supported on horizontal hinges at the abutments. With the help of hydraulic jacking equipment, two prefabricated ribs can be rotated horizontally to the closure position. The vertical swing method begins also with fabricating two half leaves of ribs on vertical hinges at abutments, but the half leaves are erected at ground level to save falsework, then rotated vertically into closure position with the hydraulic jack equipment. The advantage of the swing method in the erection process during construction of a CFST arch bridge over a railway or a frequently used waterway is that traffic disruption is minimal. Sometimes, a combination of both the horizontal and the vertical swing method is used during the erection of one CFST arch bridge. The Yajisha Bridge was erected by a combination of the vertical and horizontal swing method. The weight of a single swing was about 13,685t, one of the heaviest weights by swing method in the world .

Yajisha Bridge, located in Guangzhou City, is an arch bridge composed of a main span of 360m CFST arch and two side cantilever half arches with 76m R. C. box arch (Fig.12). It was the largest span CFST arch bridge in China at that time. The deck of the bridge is 32.4m wide, including dual 3 lanes for vehicle traffic. The bridge was erected by using swing construction method, and was constructed from Aug., 1998 to June, 2000.



Figure 12 : Yajisha Bridge in Guangzhou

The arches are fixed on the piers and the bridge is tied by the pre-stressed steel bar from two ends of the side spans. There are two arch ribs in the main span. The arch axis is an inverted catenary curve. The calculation span is 344m and the rise of the arch is 76.45m. The ratio of rise to span is  $1/4.5$ . Each arch rib is composed of six steel tubes of 750mm diameter filled with C60 concrete each. Both the upper three tubes and the lower three ones are connected with two steel plates in the level, and where C60 concrete was filled. The vertical and the diagonal web members of the arch truss are made up of steel tubes also. The width of the rib is 3.45m and the height varies from 8.039m at the arch ends of to 4.0m at the crown.

It is 35.95m wide center-to-center of the two ribs, connected to form a spatial large frame by seven groups of lateral sway steel tubular truss bracings, which consist of both the struts and diagonals. The web tube diameter of the struts and the diagonals is 299mm and the wall is 8mm thick. The tube diameter of the chord of the strut and diagonal trusses are 500mm and 450mm, respectively. Two bracing groups are in the part of the arch ribs under the deck and the other fives are in the part of the arch rib overhead the deck.

The two side spans are deck bridges of cantilever half arch. The arch ring is a box rib of 4.5m height and 3.45m wide. It is a stiffened skeleton concrete box, which is made up of CFST members. Between the two ribs of each side span, there are also lateral sway bracings of steel tubular trusses and reinforcement concrete lateral end girders to connect them to form a spatial frame. The arch axis of the side span is also inverted catenary curve with a curve coefficient of 2.0. The ratio of rise to span is  $1/5.2$ .

Wushan Yangtze River Bridge, located in the Reservoir of Three Gorges, completed in March, 2005 (Fig.13), is a half-through CFST arch bridge with a clear span of 460m and a rise to span ratio of  $1/3.8$ . It breaks the longest span record of 360m of CFST arch bridge, more than 100m longer than Yajisha Bridge .



Figure 13 : Wushan Yangtze River Bridge

The bridge width is 19m, in which 15.0m for traffic lane and  $2 \times 1.5\text{m}$  for walkways as well as  $2 \times 0.5\text{m}$  for rails. The arch ribs are twin of CFST trusses. The axis is a catenary curve with a parameter of 1.55 m. The width of a rib is 4.14m; its height of the rib varies from 7.0m in crown to 14.0m in the spring. The center distance of the two ribs is 19.7m. Four chord members in each rib are steel tubes  $\Phi 1220 \times 22\text{mm}$  filled with C60 concrete. The vertical and the diagonal web members are made up of steel tubes  $\Phi 610 \times 12\text{mm}$ . The lateral bracing members of the CFST chords are also hollow steel tubes of  $\Phi 711 \times 16\text{mm}$ .

Total of 20 lateral bracings connect the two parallel arch ribs together. Except two bracings at the intersection point of deck to arch ribs are composite structures of steel tubular and steel plate girder, the other bracings are steel tubular trusses, in which the bracings upper the deck are in K-shape and the bracings below the deck are in a shape combined of two K.

The hangers are high strength parable wires of  $109\Phi 7\text{mm}$ ,  $R_{yb}=1670\text{Mpa}$ . The spandrel columns are CFST columns of  $\Phi 920 \times 12\text{mm}$  steel tubes filled with C50 concrete. The cross beams are pre-stressed concrete T-shaped with height of 2.11m in middle part and 1.22m in support part. The distance between two cross beams are 12.0m. The pre-fabricated reinforced concrete "I"-shaped beams are laid on the top of the cross beams and the CSI-concrete put them together to form the deck.

The split abutment for each rib is located in the rock foundation. Two-split abutments at one side bank are combined together by three reinforced concrete beams. The steel tubular arch was erected using cable crane method. Each arch rib is divided into 11 hoisting elements and each bracing is a hoisting element. The heaviest hoisting element weighs 128t and the design hoisting capacity is 170t. The span of the cable crane is 576m with the height of the tower of 150.22m. The hoisting member from the water level to the structure level is as high as about 260m. The bridge was constructed from December 2001. The steel tubular arch was closed on April 17, 2003. The concrete was filled into the steel tube from October 29, 2003. It was completed in 2004.

Zhijinghe Bridge is an important bridge in the express way from Yichang to Enshi, Hubei Province. The bridge crosses over a very deep gorge, connecting two tunnels at two sides. The main span of the bridge is a deck CFST arch bridge with a span of 430m, its approaches are simply-supported prestressed concrete box beams. The foundation of the abutments is spread foundation while the foundation of the piers of the approaches are piles. The piers of the approaches and the spandrel columns of the main arch bridge are reinforced concrete solid or box columns. The deck pavement consists of 9cm thick asphalt concrete and 8cm thick waterproof concrete. Four deck expansion joints are set on the two abutments and two spring spandrel columns.

The rise of the main arch is 78.18m and the rise-to-span ratio is 1/5.5. The arch axis is a catenary with a parameter of 1.756. The two truss arch ribs has a central distance of 13m, and each one is 4m wide, with a varying depth from 6.5m at crown to 13m at springing. The CFST chord is 1200mm in diameter with 35mm thick wall, filled with concrete C50. The spandrel columns are of laced structure composed of box section of  $1400\text{mm} \times 1000\text{mm}$ , and the height is varying from 3.153m to 71.866m. The deck is continuous over 22 spans, with every span of 21~21.4m. The prestressed concrete girders are initially simply-supported, and made continuous over intermediate supports. The bridge construction was completed in 2009, see Fig.14.

Today, there are many CFST arch bridges under construction or design, for example, a CFST half-through arch bridge in highway with a span of over 500m is under construction today, and a CFST deck arch bridge in railway with a span near 400m is under construction.

Although CFST arch bridges have been developing quickly in China since 1990, the theoretical research of this structure lags far behind the application. Therefore, researches on design theory and construction techniques have become hot topics those days in China, which are supported by many funds and engineering projects. The design code of CFST arch bridge is underway and will be issued for enforcement in 2012 by the Transportation Ministry of China as planned. All those work will definitely improve the design theory and construction techniques and CFST arch bridges are expected to be built more reasonably and economically in the future.



Figure 14 : Zhejinhe Bridge near completed

## 6 CONCLUSIONS

Stone arch bridges have taken important roles in road systems in Chinese history. However, it is heavy, labor consuming and difficult to build and is not an economic bridge type to be considered at present in many cases. The maintenance, rehabilitation and strengthening of these stone arch bridges have become a very important topic in China. Bridge management authority and engineers should pay enough attention to these in-service bridges and learn from research results and engineering experience carried out in other countries.

Compared with other types of bridges in China at present, steel arch bridges are still very expensive to be built. Its fabrication techniques and design experience are still at a relatively low level. Therefore, it is unseasonable to build too many large steel arch bridges in China at present.

Great effort to improve structure and construction techniques of concrete arch bridges has been made and great achievements on this type bridge have been obtained by Chinese bridge engineers. In mountain area, when bridges cross over V-shaped or U-shaped valleys, concrete arch bridges are still suitable and economic to be used with spans from 30m-200m. Due to the construction difficulty and material consumption increase with the arch span, research should be focused on new structure type, high strength and lightweight materials as well as erection methods in super-long span concrete arch bridges.

CFST arch bridges have been developing quickly since 1990. The code for design and construction techniques of CFST arch bridge will be published soon after. The researches on design theory, construction techniques, structural detail design have become hot topics these days in China and are financially supported by many funds and engineering projects. All those work will definitely improve the design theory and construction techniques and CFST arch bridges are expected to be built more reasonably and economically in the future.

Heading to the 'golden age' for bridge construction, the Chinese engineers are well prepared and will cooperate with our colleagues from all over the world to meet the challenge of the largest scale bridge construction of the world in the new century with new structure, new material, new technique and new equipment as well as innovative management.

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